

The Role of Quench-back in the Passive Quench Protection of Long Solenoids with Coil Sub-division

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Abstract—This paper describes how a passive quench protection system can be applied to long superconducting solenoid magnets. When a solenoid coil is long compared to its thickness, the magnet quench process will be dominated by the time needed for quench propagation along the magnet length. Quench-back will permit a long magnet to quench more rapidly in a passive way. Quench-back from a conductive (low resistivity) mandrel is essential for spreading the quench along the length of a magnet. The mandrel must be inductively coupled to the magnet circuit that is being quenched. Current induced in the mandrel by di/dt in the magnet produces heat in the mandrel, which in turn causes the superconducting coil wound on the mandrel to quench. Sub-division is often employed to reduce the voltages to ground within the coil. This paper explores when it is possible for quench-back to be employed for passive quench protection. The role of sub-division of the coil is discussed for long magnets.

Index Terms—Magnet Quench-back, Coil Sub-division

1. INTRODUCTION

Quench-back is a widely used passive quench protection method that enhances the rate of propagation of the normal zone by using a coupled secondary circuit. As quenching proceeds, the secondary will heat up. If it is in good thermal contact with the magnet winding, it will initiate further quenching—effectively increasing quench propagation velocity and therefore reducing the hot spot temperature. It is particularly effective in a situation where the normal zone hits boundaries rather early in the quenching process and thereafter spreads very slowly in the other dimension [1-3].

Sub-division provides an alternative path for some of the current by connecting shunt resistors across sections of the magnet, and the shunt resistor can absorb some of the stored energy in the coil. So the hot spot temperature of the coil can

be reduced by this technology. The shunt resistors across the sub-division can balance the overvoltage in the coil, so the voltage to ground in the coil can be limited and reduced [1][4].

This paper describes a passive quench protection system that may be applied to a long superconducting solenoid with sub-division. The role of quench-back in the quench protection of such a solenoid is discussed.

1. PASSIVE QUENCH PROTECTION OF A LONG SOLENOID

A. Long Solenoid Parameters

The solenoid discussed in this paper is a spectrometer magnet used in the MICE project, shown in Fig. 1 [5]. This magnet consists of two match coils M1 and M2 and three-coil spectrometer section (E1, C, and E2). M1 and M2 are used to match the spectrometer section with the MICE cooling channel. The three-coil section produces a uniform magnetic field (± 0.3 percent) within a region that is 1000 mm long and 300 mm in diameter. The uniform field section contains a five-plane scintillating fiber detector for muon beam emittance analysis. The magnet has an Nb-Ti superconductor with a copper to superconductor ratio of four. The insulated conductor dimensions are 1.65 by 1.00 mm. All five coils are wound on a single 6061-T6-aluminum mandrel. The cryostat consists of 4.2 K helium vessel, an 80 K thermal shield, cold mass supports for 500 kN and a 300 K vacuum vessel.

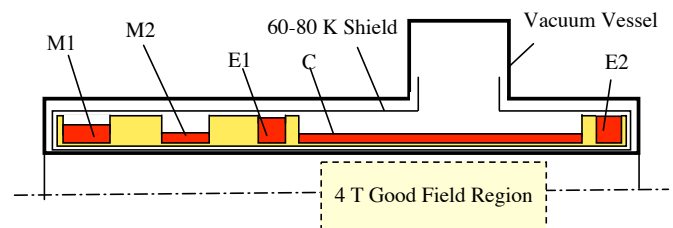


Fig. 1 A Schematic Cross-section of the MICE Spectrometer Solenoid

The spectrometer section coil C is long compared to its thickness. This paper mainly focuses on this coil and coils E1 and E2 that are in series with it. The spectrometer section design parameters are shown in Table 1. In Table I, Z1 and Z2 are the axial distances from the match coil end of the cold mass to the two ends of the coil. The coil length is $Z2 - Z1$; R1 is the coil inner radius; and R2 is the coil outer radius. The coil thickness is $R2 - R1$.

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TABLE 1. THE PARAMETERS FOR THE THREE COIL SECTION OF THE MICE SPECTROMETER SOLENOID [4]

Parameter	E1	C	E2
No. Turns/Layer	64	768	64
No. Layers	56	20	62
Z1 (mm)	908.7	1056.9	2408.7
Z2 (mm)	1019.3	2371.2	2519.3
R1 (mm)	258.0	258.0	258.0
R2 (mm)	319.7	280.4	326.3
Z2 – Z1 (mm)	110.6	1314.3	110.6
R2 – R1 (mm)	61.7	22.4	68.3
Self Inductance (H)	15.39	51.58	15.91
Design Current (A)	226.6	269.9	240.7
Stored Energy (MJ)	0.40	1.88	0.46

B. Quench Protection of the Long Solenoid

Fig. 2 shows a design case for the charging and the quench protection circuit for the matching section and three coil spectrometer section for a MICE spectrometer solenoid. Each match coil will be powered by a power supply that delivers 300A at 10V. The magnet discharge will be through a diode pack. The three-coil spectrometer solenoids are connected in series using a single 300A power supply that delivers a voltage up to 10V. The end coils E1 and E2 will be adjusted using a pair of power supplier that will deliver 60 A at 5V.

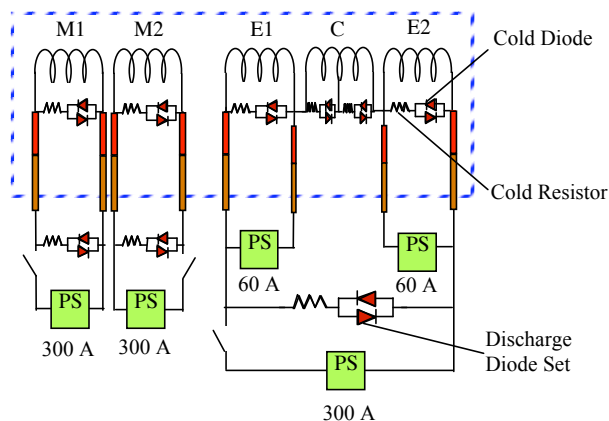


Fig.2 Quench protection circuit for the MICE spectrometer solenoids

The magnet quench protection is passive. The two match coils each have back-to-back diodes and a resistor across them. This reduces the hot spot temperature in coils M1 and M2. The end coils E1 and E2 of the three-spectrometer coil set also have back-to-back diodes and a resistor across them. The center (C) solenoid of the spectrometer solenoid set is subdivided in two parts. Thus the three-coil spectrometer section has a total of four sub-divisions (see Fig.2).

The match coils are not a problem during a quench of the spectrometer magnet. In both case the stored energy of these coils is low (less than 0.5 MJ) [5]. Because the stored energy is low, the peak voltage to ground is also low. The hot spot temperature of the two match coils will also quite low because the two match coils will become totally normal in about 2 s.

The three-coil spectrometer solenoid has a total stored energy of 2.81 MJ. The center coil is 1.314 meters long. A quench induced at one end of the long center coil will take more than twelve seconds to propagate to the other end. The hot-spot temperature of the center coil is higher because the time for the magnet to become fully normal is long. From a quench standpoint, only the three-coil spectrometer section is of interest.

Coil C, which is in series with the coils E1 and E2, is long compared to its thickness as shown in Table 1. Quench-back can play an important role in this coil, because without quench back the coil C quench process will be dominated by the time needed for quench propagation along the magnet length. The mandrel is inductively coupled to the magnet circuit that is quenching. Current induced in the mandrel by di/dt in the magnet produces heating in the mandrel, which in turn causes the superconducting coil wound on the mandrel to quench. Quench-back speeds up the quench process in coil C, and thus reduces the hot spot temperature. Sub-division of the spectrometer section is used to reduce the voltage to ground.

II. COMPUTATION RESULTS

A. Computation Model description

A semi-empirical quench model considering both the sub-division and quench-back is developed to study the quench process of the spectrometer solenoids quench process. A quench is initiated in the lower left corner of solenoid C and starts to expand in the three directions with velocities v_ϕ (longitudinal propagation along the wound conductor), v_r (radial propagation) and v_z (axial propagation). In the model, average constant quench propagation velocities in three directions based on an experiment correlation are used during quench process, v_ϕ is 4.519 ms^{-1} , v_r is 0.065 ms^{-1} and v_z is 0.105 ms^{-1} [6]. The power supply is shut off during the quench.

The normal zone shape is assumed to be an ellipsoid. The calculation proceeds in time steps of Δt . At each step another layer is added to the surface of the normal zone like the skin of an onion. After a time step the current will have decayed. The calculation processes proceeds until the current in each coil is less than the 1 percent of the starting current [7]. For the quench-back modeling, the key parameter is the time when the new normal zone induced by the heat from the mandrel appears. This time is the sum of two time periods.

The first time period is the time for the mandrel to heats up to $\sim 10 \text{ K}$. This time is associated with the current shift from the coil to the mandrel. This time is a function of the mandrel resistivity and volume specific heat [2].

The second time period is the time for heat to flow from the mandrel to the superconductor through the insulation. The time constant for the heat to flow from the mandrel to the coil is influenced by how the much of the coil is in contact with the mandrel. Because, the quench velocity around the coil is large, the contact effect of not having complete coverage is not as great as one would expect. After quench-back occurs, the normal zone is the combination of the normal zone induced by the coil's quench propagation plus the normal zone induced by quench-back [2][3].

B. The Role of Quench-back and Mandrel Material

The quench process in the three-coil section is affected by the mandrel material. A low resistivity mandrel leads to a faster mandrel temperature rise to a specific value (~ 10 K), so the quench back from the mandrel will occur earlier. Three mandrel materials 1100-0 Al, 6061-T6 Al and 304 stainless-steel (304 SS) were studied to explore the role mandrel material quench back. In this case, coils E1 and E2 each had one sub-division; coil C had two sub-divisions (see Fig.2). The cold resistor across each section is 0.02Ω .

Fig. 3 shows that the hot spot temperature varies with the mandrel material. With 1100-0 Al, 6061-T6 Al and 304 SS, the hot spot temperatures are 159 K, 204 K and 255 K respectively. Because the center coil is long, the time for the quench propagating from one end to the other end is ~ 12.5 s, without quench-back. In our calculation we found that quench-back from the mandrel starts ~ 1.4 s after the quench start with an 1100-0 mandrel and ~ 2.0 s after the quench start for a 6061-T6 mandrel. Because 304 SS has a high resistivity and specific heat, quench-back did not occur. The theoretical quench-back start time is proportional to the mandrel resistivity times the material enthalpy change per unit volume to the $1/3$ power plus the time it takes for the heat pulse to cross the insulation layer. After quench-back starts, a new normal zone propagates in the radial direction. The center coil becomes fully normal ~ 0.34 s after quench back starts. In a long coil, early quench-back can result in a much lower coil hot spot temperature than it does in a short coil [4].

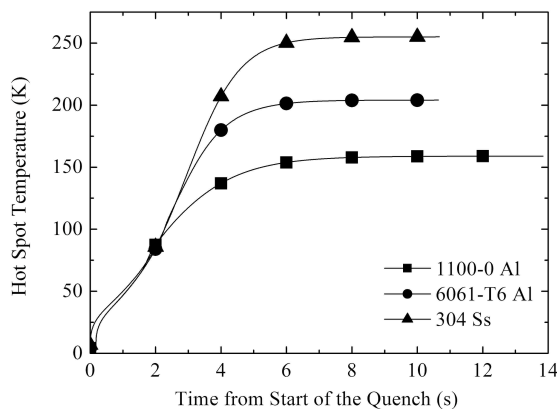


Fig. 3. Hot spot temperature with different mandrel material

Fig. 4 shows the peak voltage to ground with different mandrel materials. With 1100-0 Al, 6061-T6 Al and 304 SS, the peak voltage to ground is 1216 V, 1768 V and 1561 V respectively. The voltage to ground used in the model is the resistive voltage across the normal zone resistance, and it is the product of the current in the sub-division and normal zone resistance in the sub-division. Quench back can cause a rapid increase in the voltage to ground in the coil, because the coil section resistance grows more rapidly. According our calculation results, the effect of the quench-back on the peak voltage to ground is at best mixed. The energy absorbed by the mandrel can reduce the voltage.. Table 2 shows the quench simulation results for the three different mandrel materials.

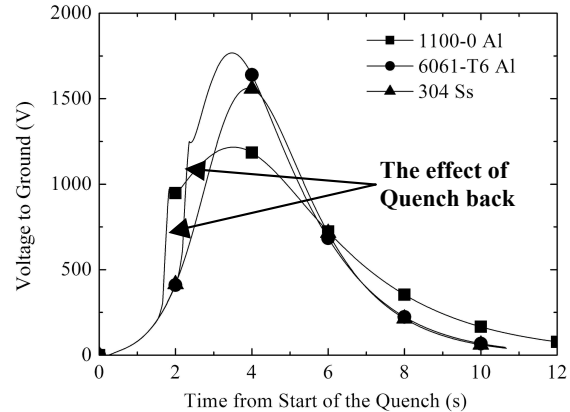


Fig. 4. Peak voltage to ground with different mandrel material

TABLE 2. QUENCH SIMULATION RESULTS WITH DIFFERENT MANDREL MATERIALS

Mandrel material	Hot spot temperature (K)	Peak voltage to ground (V)
1100-0 Al	159	1216
6061-T6 Al	204	1768
304 SS	255	1561

C. The role of Magnet sub-division

The role of sub-division in the quench protection of three-coil spectrometer section was studied. The three cases studied had quench back (after ~ 2 s) from the 6061-T6-aluminum mandrel. In case 1, E1, E2 have one sub-division each, and C has two sub-divisions. The three coils have a total of four sub-divisions as shown in Fig. 2. In case 2, E1, E2 and C have one subdivision each. The three coils have three sub-divisions. In this case, E1, E2 and C are connected in series with one resistor and diode across them. In case 3 the initiation currents of E1 and E2 are same as that of the C (270 A). In all the cases, the cold resistor across each sub-division is 0.02Ω .

Hot spot temperature with 4, 3 and 1 sub-divisions (cases 1, 2 and 3) for the three coils is 204 K, 216 K, and 197 K respectively. It appears that the number of subdivisions within the three-coil magnet section has only a small effect on the hot spot temperature of the hottest coil. From Fig. 3, it is clear that the mandrel material has a far bigger effect on hot spot temperature than does the number of magnet sub-divisions.

Fig. 5 shows the voltage-to-ground for different numbers of magnet sub-division numbers. The peak voltage to ground with 4, 3 and 1 sub-divisions (cases 1, 2, and 3) in the coil set is 1768 V, 3530 V and 6127 V respectively. The sub-division of the center coil has a particularly large effect on the voltage. This is because voltage to ground is the product of the current in the sub-division and normal zone resistance in the sub-division. The resistance in each sub-division decreases as the number of sub-divisions increase. Fig. 5 shows that the sub-division number has significant effect on decreasing the voltage to ground.

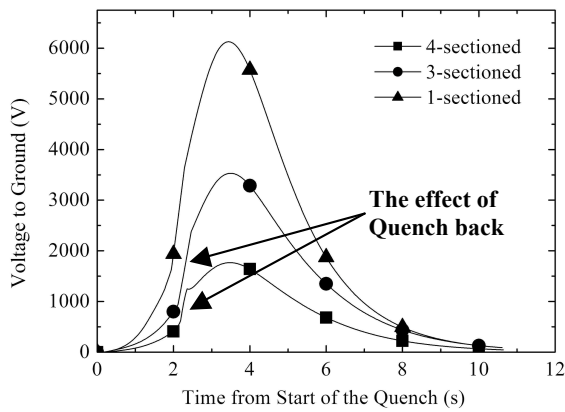


Fig. 5. Peak voltage to ground with different sub-division number

D. The effect of the shunt resistance

The effect of the shunt resistance on the quench process was also studied. Fig. 6 shows the hot spot temperature with different shunt resistances across the sub-divisions. The hot spot temperature with a 0.02- Ω resistor is 204 K, and the hot spot temperature with 1.00- Ω resistor is 101 K. This is because a larger shunt resistance will absorb more energy from the magnet circuit during quench process. From our calculations, each 1.00- Ω resistor absorbs about 170 kJ of the magnet stored-energy during quench process. In addition, the shunt resistance across the magnet coils decreases the time at which quench back is initiated (see Fig 7).

Fig. 7 shows the peak voltage to ground with two different shunt resistances. The peak voltage to ground with a 0.02- Ω resistor is 1768 V; The peak voltage to ground with a 1.00- Ω resistor is 1536 V. This is because a large shunt resistance induces faster current decay (and quench-back) and slows the growth of the normal zone resistance. Both of these factors lead to a lower peak voltage to ground for the case where the resistance is 1.00 Ω .

The 1.00- Ω resistor mass must be as large as 1.9 kg to keep its temperature below 300 K at the end of the quench. The shunt resistor mass is proportional to its resistance.

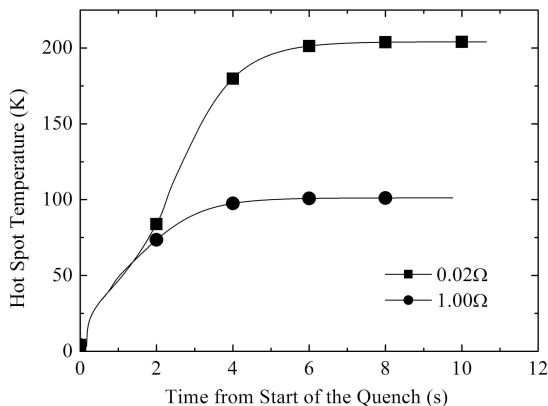


Fig. 6. Hot spot temperature with different shunt resistances

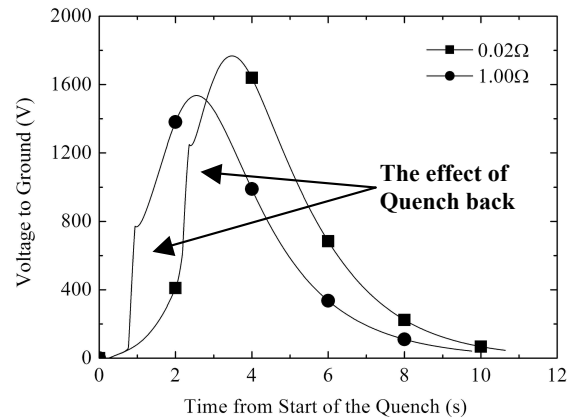


Fig. 7. Peak voltage to ground with different shunt resistances

III. CONCLUSION

A semi-empirical model was developed to study the quench process of the solenoid. The calculation results show that quench-back increases the quench propagation rate within the coil greatly and it reduces the time the magnet needs to become fully normal. Quench-back reduces the hot spot temperature in the coil, but it may increase the peak voltage to ground because the quench is faster. Increasing the sub-division number reduces the voltage to ground, but its effect on the hot spot temperature is usually small. A large shunt resistance across each sub-division can reduce the magnet hot spot temperature and voltage to ground, because a large shunt resistance will absorb magnet energy during quench. A large shunt resistor also speeds up quench-back. The shunt resistance mass must increase with resistance in order to keep its temperature below 300 K. The three-coil spectrometer set with its four sub-divisions can quench safely by means of quench-back from the mandrel, even when the shunt resistance is very low. This has been demonstrated experimentally [8]. The diodes across the coils protected the magnet when an HTS lead burned out during the test of one of the magnet.

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